Physique des Particules

Federico Ferri

CEA-Saclay Irfu-SPP

Présentation du département P2I de l'Université Paris-Saclay
January 22, 2015

Représentants thématique Physique des Particules

Vincent Boudry (LLR), Gautier Hamel de Monchenault (Irfu),
Frédéric Machefert (LAL), David Rousseau (LAL), Marco Zito (Irfu)

Laboratories

- **Several strongly inter-connected laboratories**
  - here only mentioned those specifically involved in particle physics

LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

- ATLAS, LHCb, ILC, FCC, (Super)Nemo
- D0, BaBar, H1

LLR

- CMS, ILC, FCC, T2K
- BaBar, H1

Irfu - CEA Saclay
Institut de recherche sur les lois fondamentales de l'Univers

- ATLAS, CMS, ILC, FCC, T2K, DoubleChooz, CeSOX, CUORE, Lumineu, GBar
- D0, BaBar, H1

CSNSM

- CUORE, Lumineu, GBar, R&D for bolometers

federico.ferri@cern.ch

Particle Physics

> *Particle physics is a modern name for centuries old effort*
> *to understand the laws of nature. . .*
>
> *Ed. Witten*

Aim at answering the following questions:

- What are the **elementary constituents** of matter?
- What are the **forces** that control their behaviour at the most basic level?

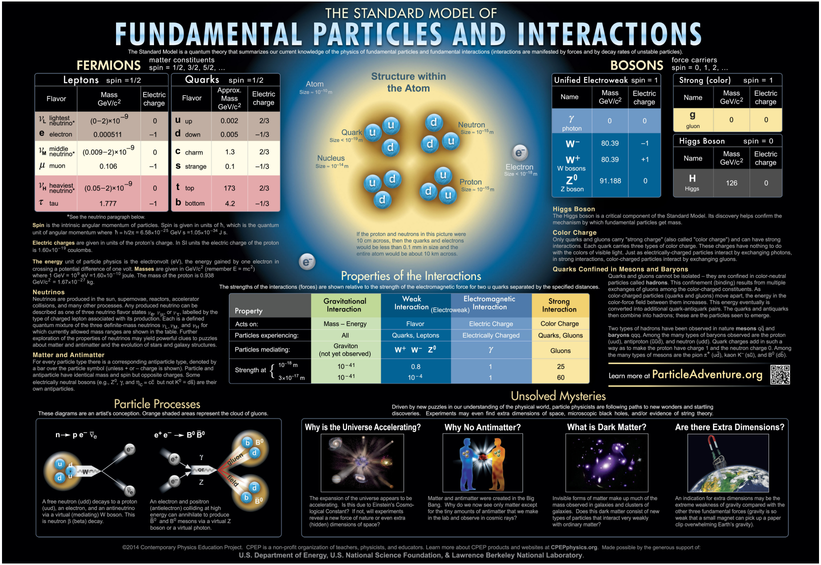
Experimental approach: [for the theoretical approach wait for 10 min]

- get particles to **interact and study the resulting products** and features. Aim at measuring the energy, the direction and the identity of these products as precisely as possible

$$\Downarrow$$

- ⋆ development of experimental techniques, R&D for particle detectors, simulations, statistical methods for data analysis, etc.
- ⋆ close (and international) collaboration with several other fields, often already part of the laboratories

The Standard Model in one slide



THE STANDARD MODEL OF

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model is a quantum theory that summarizes our current knowledge of the physics of fundamental particles and fundamental interactions (interactions are manifested by forces and by decay rates of unstable particles).

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-2)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-2)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.05-2)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

*See the neutrino paragraph below.

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $=1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The energy unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$) where 1 GeV = 10^9 eV $=1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.

Neutrinos

Neutrinos are produced in the sun, supernovae, reactors, accelerator collisions, and many other processes. Any produced neutrino can be described as one of three neutrino flavor states ν_e, ν_μ, or ν_τ, labelled by the type of charged lepton associated with its production. Each is a defined quantum mixture of the three definite-mass neutrinos ν_L, ν_M, and ν_H for which currently allowed mass ranges are shown in the table. Further exploration of the properties of neutrinos may yield powerful clues to puzzles about matter and antimatter and the evolution of stars and galaxy structures.

Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$ but not $K^0 = d\bar{s}$) are their own antiparticles.

If the proton and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Higgs Boson spin = 0

Name	Mass GeV/c^2	Electric charge
H Higgs	126	0

Higgs Boson

The Higgs boson is a critical component of the Standard Model. Its discovery helps confirm the mechanism by which fundamental particles get mass.

Color Charge

Only quarks and gluons carry "strong charge" (also called "color charge") and can have strong interactions. Each quark carries three types of color charge. These charges have nothing to do with the colors of visible light. Just as electrically-charged particles interact by exchanging photons, in strong interactions, color-charged particles interact by exchanging gluons.

Quarks Confined in Mesons and Baryons

Quarks and gluons cannot be isolated – they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs. The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge.

Two types of hadrons have been observed in nature **mesons** $q\bar{q}$ and **baryons** qqq. Among the many types of baryons observed are the proton (uud), antiproton ($\bar{u}\bar{u}\bar{d}$), and neutron (udd). Quark charges add in such a way as to make the proton have charge 1 and the neutron charge 0. Among the many types of mesons are the pion π^+ ($u\bar{d}$), kaon K^- ($s\bar{u}$), and B^0 ($d\bar{b}$).

Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property		Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:		Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:		All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:		Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at	10^{-18} m	10^{-41}	0.8	1	25
	3×10^{-17} m	10^{-41}	10^{-4}	1	60

Learn more at **ParticleAdventure.org**

Particle Processes

These diagrams are an artist's conception. Orange shaded areas represent the cloud of gluons.

$n \rightarrow p\, e^- \bar{\nu}_e$

A free neutron (udd) decays to a proton (uud), an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β (beta) decay.

$e^+ e^- \rightarrow B^0 \bar{B}^0$

An electron and positron (antielectron) colliding at high energy can annihilate to produce $\bar{B}^0$ and B^0 mesons via a virtual Z boson or a virtual photon.

Unsolved Mysteries

Driven by new puzzles in our understanding of the physical world, particle physicists are following paths to new wonders and startling discoveries. Experiments may even find extra dimensions of space, microscopic black holes, and/or evidence of string theory.

Why is the Universe Accelerating?

The expansion of the universe appears to be accelerating. Is this due to Einstein's Cosmological Constant? If not, will experiments reveal a new force of nature or even extra (hidden) dimensions of space?

Why No Antimatter?

Matter and antimatter were created in the Big Bang. Why do we now see only matter except for the tiny amounts of antimatter that we make in the lab and observe in cosmic rays?

What is Dark Matter?

Invisible forms of matter make up much of the mass observed in galaxies and clusters of galaxies. Does this dark matter consist of new types of particles that interact very weakly with ordinary matter?

Are there Extra Dimensions?

An indication for extra dimensions may be the extreme weakness of gravity compared with the other three fundamental forces (gravity is so weak that a small magnet can pick up a paper clip overwhelming Earth's gravity).

CPEP is a non-profit organization of teachers, physicists, and educators. Learn more about CPEP products and websites at **CPEPphysics.org**. Made possible by the generous support of:
U.S. Department of Energy, U.S. National Science Foundation, & Lawrence Berkeley National Laboratory.

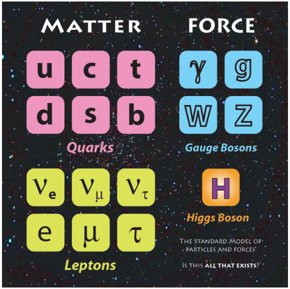
The Standard Model in a different slide

...	...
1974	quark c
1976	lepton τ
1978	quark b
1979	gluon
1983	Z^0 et $W^{\pm}$ bosons
1990	three families of light ν
1995	quark t
2012	Higgs Boson (not in the picture!)
...	...

Extraordinary predictive theory, and arguably one that is most precisely tested.

- **discoveries** are only part of the story
- the complementary part are **precise measurements**

Activities: a possible categorization



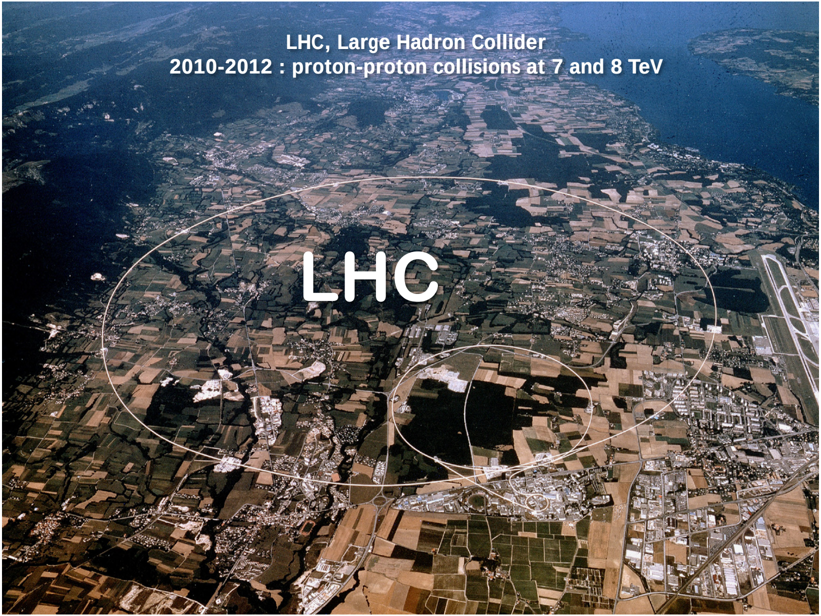
Some fundamental questions:

- why three families?
- why such large mass differences?
- where is the anti-matter in the universe?!
- where is the matter??!!!
- how do gauge bosons (and particles) get a mass?
  - ✓ where is the Higgs Boson?
- ...

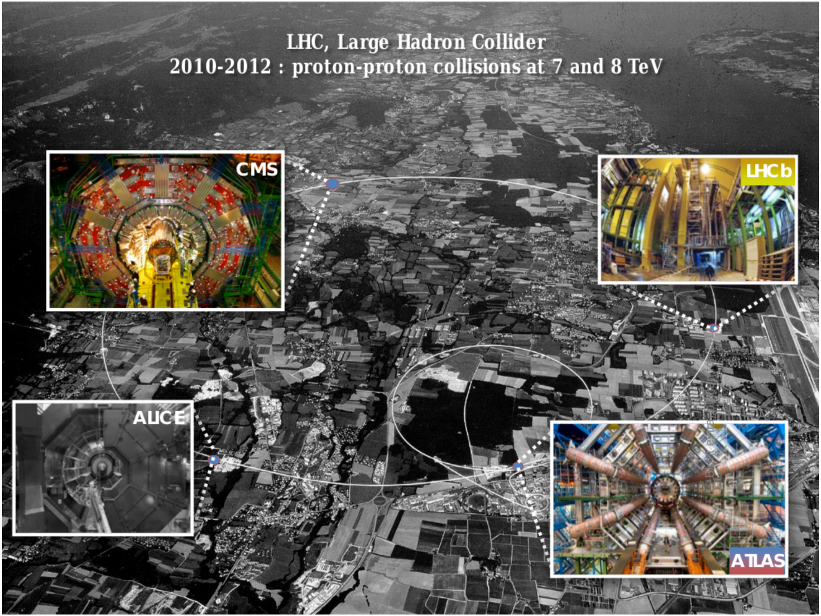
- **High energy (mostly collider) experiments**: ATLAS, CMS, LHCb, ILC, FCC, HL-LHC
  ALICE: 10 min ago
- **Neutrino experiments**: T2K, DoubleChooz, CeSOX, Stereo, (Super)Nemo, neutrinoless double β decay
- **Others**: e.g. GBar, R&D for future experiments and detector techniques, etc.

N.B. Some experiments running, some being built, some being thought about...

High-Energy experiments: LHC



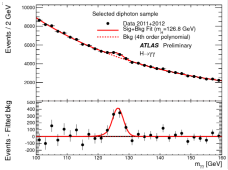
High-Energy experiments: LHC detectors

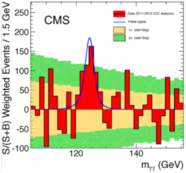


High-Energy experiments: LHC highlights

$H \to \gamma\gamma$

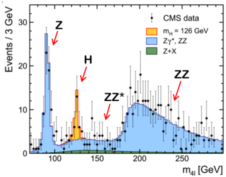
ATLAS: LAL; CMS: Irfu

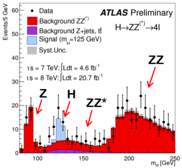




$H \to ZZ \to 4\ell$

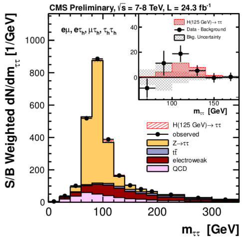
CMS: LLR; ATLAS: LAL, Irfu





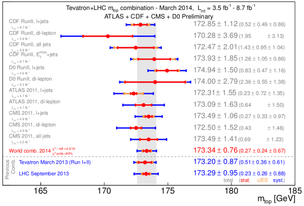
$H \to \tau\tau$

ATLAS: LAL; CMS: LLR



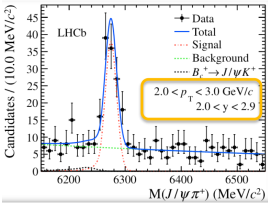
World top mass combination

ATLAS, D0: Irfu



$B_c^+ \to J/\psi\pi^+$

LHCb: LAL



- $H \to WW$, $H \to bb$ (LAL), Standard Model physics with $\gamma\gamma$, WW, ZZ, ZW, $\tau\tau$ final states (LLR, Irfu, LAL), CKM triangle (LAL), etc.
- as well as Heavy Ion program (LLR, Irfu) [see 10 min ago]

High-Energy experiments: the future

- **HL-LHC** 2025+: adapt the detectors to an **increased LHC luminosity** (×10 w.r.t. 7-8 TeV Run, ×5 w.r.t. 13 TeV Run)
  - Phase1 ≈ 2018 (ATLAS: LAL, Irfu): electronics, muon wheels
  - Phase2 ≈ 2025 (ATLAS: Irfu, LAL; CMS: Irfu, LLR): electronics, trigger, (very) forward calorimetry

- **ILC** (Irfu, LAL, LLR) 2027+: build a **linear collider** for precision physics (Higgs or beyond SM)
  - some of the detector technology developed for ILC can be adapted to the upgrade of the LHC experiments (e.g. CMS forward calorimetry, LLR)

- **FCC** (Irfu, LAL, LLR) 2035+: build a new **circular collider** ($\mathcal{O}(100)$ km) at higher energies for precision physics and discovery (à la LEP + LHC: 90-400 GeV leptons, 100 TeV hadrons)

federico.ferri@cern.ch

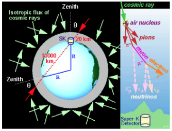
Neutrino Physics

Neutrino oscillations

sun

reactors

atmosphere

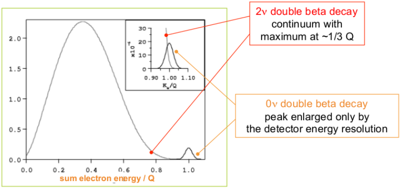


accelerators

- Long baseline accelerator: T2K (Irfu, LLR)
- Reactors: Juno (LLR)
- Search for a sterile ν 1. at reactors: DoubleChooz, Nucifer, Stereo (Irfu) 2. with a source: CeSOX (Irfu)

Double beta decay

- Cuore (CSNSM, Irfu), (Super)Nemo (LAL), Lumineu (CSNSM, Irfu)
- R&D on bolometers (CSNSM, Irfu)

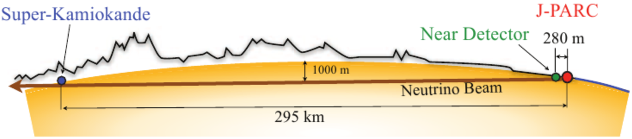


2ν double beta decay
continuum with
maximum at ~1/3 Q

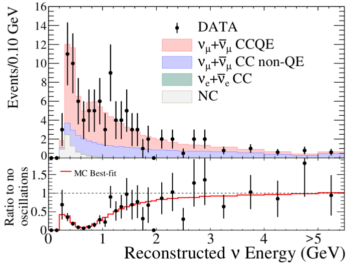
0ν double beta decay
peak enlarged only by
the detector energy resolution

federico.ferri@cern.ch

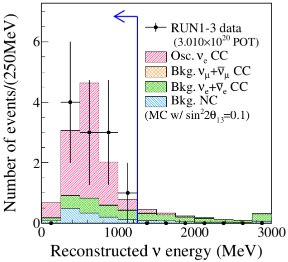
Neutrino Physics: T2K



ν_μ disappearence



ν_e appearence



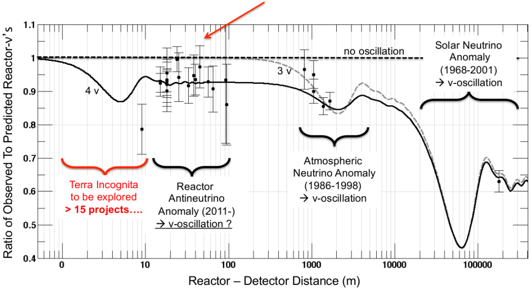
- Contributions to analysis and near detectors: off-axis (Irfu), on-axis (LLR)

Also pro-active in the future long-baseline programs, such as LAGUNA, exploring LBNF in the USA and HK in Japan (CP violation studies)

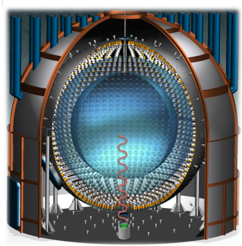
Neutrino Physics: search for a sterile ν

Motivated by a reanalysis of 19 published reactor results at short distance (10-100 m), with new inputs from Double Chooz: 7% deficit (Irfu)

- **Observed/predicted averaged event ratio: R=0.938±0.023 (2.7 σ)**



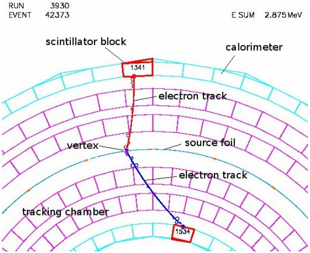
- Confirm the reactor ν anomaly: Nucifer (Irfu)
  - also develop detection technology for reactor monitoring with commercial components
- Improve reactor experiments by going closer and by measuring the energy spectrum along the detector axis: Stereo (Irfu) [2015-2018]
- Innovate: CeSOX, an anti-ν source at Borexino (Irfu) [2013-2018]

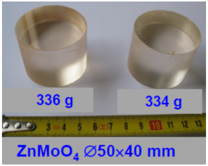


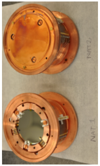
Neutrino Physics: neutrinoless double β decay

Determine the **Dirac or Majorana nature of neutrinos**: search for very rare events in a low background environment (underground: LSM, Modane).

- Nemo3 and SuperNemo (LAL): 5 kg of enriched and purified double β emitting isotope (considering ^{82}Se, ^{150}Nd, ^{48}Ca)





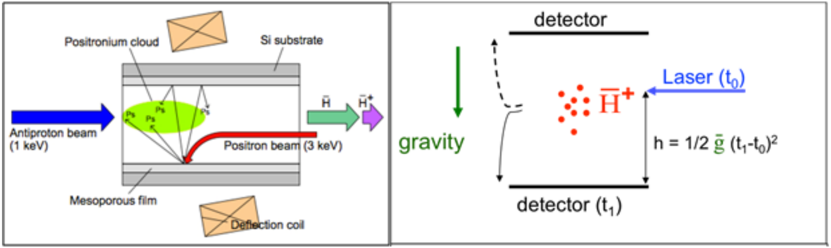


- Lumineu (CSNSM, Irfu): development of a scintillating bolometer (heat + scintillation) using Zn ^{100}MoO$_4$
  - 0.68 kg in 2015, then 10 kg demonstrator
- CUORE (CSNSM, Irfu): ^{130}TeO$_2$ bolometers at LNGS, Gran Sasso

federico.ferri@cern.ch

This was not an exhaustive list, e.g. GBar

Gravitational Behaviour of Antihydrogen at Rest: **direct measurement of the free-fall acceleration of antihydrogen** atoms in the terrestrial gravitational field (CSNSM, Irfu)



- Precision: 37% with single measurement, 1% with 1500 events (few weeks), **final goal of 0.1%**
- to be installed at CERN Antiproton Decelerator, taking data from 2017

Summary

- **Major research axes of Particle Physics well covered within the laboratories of P2I**

- **Significant impact within the international collaborations**
  - both in term of results and responsibilities

- **Close interaction with several other fields** (theory, detectors, accelerators and magnets, nuclear physics, data analysis, etc.)

federico.ferri@cern.ch